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Soil & Tillage Research 47 (1998) 275–290

Soil & Tillage Research

Future yield growth in field crops: what evidence exists?

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Abstract

Crop yields are an important determinant of C input into the soil and ultimately of soil organic carbon (SOC). Models to predict changes in SOC require crop yield and future yield growth information. In this review, yield trends for 11 major crops in the US for the period 1939–1994 are analyzed. Historical data are analyzed to detect evidence of a yield plateau. Yields are extrapolated to the year 2020 based on linear and exponential yield trends estimated in the paper. Forward-looking information on yield gaps, on the biological potential for future yield growth, and socio-economic determinants of yield growth is examined for evidence that yield growth may plateau in the near future. A linear model of yield growth indicates a compound annual rate of growth of between 0.7% and 1.3% per year for major US crops through 2020. Under an exponential model, growth rates could range up to 3% per year. This could lead to substantial increases in SOC if crop residues are retained. Biophysical limits, including those imposed by agronomic and tillage practices, do not appear to prevent rates of growth consistent with the linear model. How socioeconomic forces will affect future growth are subject to greater uncertainty.

Keywords: Crop yields; Soil carbon sequestration; Agricultural research

1. Introduction

Total biomass production is an important determinant of C input into soils which, in turn, is a major determinant of levels of soil C. Paustian et al. (1997) found that for a given climatic region and soil type, the rate of C input is an important factor determining the amount of C which can be maintained in the soil, noting that residue inputs are highly controlled by the farmer via crop selection, productivity (yield) levels, residue management, and the use of manure. They show a strong linear relationship between C input and soil organic matter (SOM). Donigian et al. (1994) note that the major source of variation in projections of soil organic carbon (SOC) for a series of forecasts to 2030 is the yield growth assumption. Over the 40 year forecast period from 1990, a yield growth rate of 1.5% per annum results in a 50% increase in SOC compared with a yield growth assumption of 0.5% per annum. Following a recommendation by Donigian et al. (1994), this paper investigates yield trends in the US in an attempt to better characterize future yield growth for the purposes of projecting SOC. Ideally, we would focus on total biomass production. Yield data, however, is more readily available for broad commercial areas than total biomass. Much of yield growth (through increased use of fertilizer, denser planting, and development of varieties that are able to take

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0167-1987/98/$19.00
PII S0167-1987(98)00116-0

advantage of highly managed conditions) is closely related to biomass production.

We begin with a review of the long-term historical record on yield growth, consider directly the recent evidence for rates of yield growth in the US for 11 major annual crops, examine the implications of extrapolating yield growth rates into the future, review evidence for biological constraints that could cause yield growth to plateau, and consider the socioeconomic factors that will affect rates of yield growth before offering our conclusions.

2. Yields: a long-term and global perspective

2.1. An historical perspective

Projecting future yields has been a subject of discussion and debate since at least the time of Malthus. His work characterized the human population as self-limiting: inevitably the food requirements of a growing population would outstrip the ability to produce food given limits on the amount of arable land. The ability to produce more per unit of land (to increase yield) was seen as, at best, delaying the inevitable shortage of food by a few years. In fact, prior to about 1700 the Malthusian model is thought to have operated, as suggested by Landes (1978) "indeed, there is good reason to believe that much of such economic growth as did take place was translated to population growth: increased income meant lower death rates, in some instances higher birth rates; and large numbers either ate up the gain or, outstripping it, set the stage for Malthusian disaster." Even so, Landes (1978) (p. 14) estimates that overall income per head probably tripled from the year 1000 to 1700 and then sharply accelerated. Some estimates of agricultural yields (grains harvested to grains planted) for the period before 1700 similarly suggest low rates of yield increase. Estimates put the increase in yield of wheat (*Triticum* sp.) per unit of seed in England over the period 1225 to 1600 as less than 0.2% per annum. Similar estimates for wheat yields in Italy between 1600 and 1700 show no consistent increase and for some areas a downward trend (Cipolla, 1976). Concern about the inability to increase production of food has continued to recur since then. Dalrymple (1980) cites Sir William Crookes (1900) as concluding that, "It is almost certain that within a generation the ever increasing population of the United States will consume all the wheat grown within its borders, and will be driven to import, and, like ourselves, will scramble for a lion's share of the wheat crop of the world."

The remarkable change that has marked economies in the modern period has been that "rapid growth was self-sustaining...for the first time in history, both the economy and knowledge were growing fast enough to generate a continuing flow that lifted beyond visible limits the ceiling of Malthus's positive checks" (Landes, 1978, p. 41). This has allowed population to expand many-fold even as living standards have generally improved. Significant increases in crop yields per hectare have been documented only since about 1940. According to Dalrymple (1980) (p. 105), US yields of wheat increased only slightly from 1866 to about 1940. This coincides with the application of crop breeding and increased use of fertilizer and other organic chemicals. Many of the earlier innovations in agriculture were mechanical innovations that were labor-saving. During this earlier period, the push-pull of reduced need for labor in agriculture and rural sectors and the increased demand for labor in the industrial and urban sectors resulted in greatly increased output per farm laborer through the ability of individual farmers to till greater areas.

In recent times, since at least the 1950s, hunger and famine has existed for some populations at some periods, but overall, the proportion and absolute number of people subject to hunger and famine around the world has declined. One estimate places the number of people suffering from chronic hunger at 786 million in 1990, down from an estimated 844 million in 1979 (Bongaarts, 1994). Kates and Chen (1994) create an index of famine that shows a four to five-fold decline since the 1950s as measured by the populations of countries where famines were reported in *The New York Times,* estimating the current population at risk between 15 and 35 million. Hunger and famine has come to be understood as a problem of a lack of income and/or rights to food rather than a problem of production (Sen, 1981). Such a rethinking of the problem of food shortage was possible because agricultural research has been successful in generating the ability to increase production with fewer inputs, in earlier years reducing labor requirements through mechanization and in more recent periods increasing yield per unit land area.

The overall conclusion is that agricultural output growth and productivity has been remarkable for probably the past 300 years. The period of documented rapid yield growth has been much shorter, extending only over the past 50 to 60 years. The sources of output and productivity growth have, thus, varied over the longer term with mechanical, biological, and chemical innovations providing the impetus and direction for change. A focus on yield growth has become more important as the availability of new land has become more limited. The extent to which it is possible to further increase cropland by converting non-agricultural land or by intensifying production on current agricultural lands (for example, by converting grazing land to cropland) remains debated. Environmental considerations and water availability appear to be a more important consideration than absolute availability of land. Post-harvest conversion and processing may also be an alternative to increased grain yields, particularly in the case of production of protein for animal feed. Post-harvest losses and the extent of livestock production can also change the relationship between grain production and the amount of food available for human consumption. Thus, the connection between yield growth of major crops and human food availability need not be as direct as it is frequently portrayed to be.

2.2. Projections

Studies of future agricultural demand and supply must, inevitably, make assumptions about future yield and productivity increases. Three major studies of the future world food situation suggest that food supply will continue to expand faster than demand over the next 20 to 30 years with world prices projected to fall (Alexandratos, 1995; Mitchell and Ingco, 1995; Agcaoili and Rosegrant, 1995). Others are, however, less optimistic citing limits on further land expansion and irrigation, resource degradation, and reduced confidence that the historical rates of increase in yield will continue (Bongaarts, 1994; McCalla, 1994; Norse, 1994).

FAO projections are illustrative of the types of yield increases implied by the global studies. As reported by Alexandratos (1995) (p. 44), world-wide average yield growth rates in FAO's projections generally declined. For example, rice (*Oriza sativa* L.) growth rates fell from the 2.3% per year during the period 1970 to 1990, to 1.5% per year from 1988–90 to 2010. A similar comparison for other crops show yield growth falling from 2.8% to 1.6% per year for wheat, from 1.8% to 1.5% per year for maize (*Zea mays* L.), from 1.5% to 1.1.% for sorghum (*Sorghum bicolor* L. Moench), and holding steady at 1.0% per year for millet (*Setaria* sp.).

Despite the importance of yield growth, work on predicting yield growth is rather limited. Most agricultural economic forecast models rely on extrapolation of historical yield trends or on underlying forecasts of base yield growth from which projected yields may vary due to commodity and input prices. The remainder of this paper will address the following: (1) examine historical trends in the US for major annual crops and discuss issues associated with forecasting trends into the future, (2) review work that has tried to go beyond trend extrapolation, and (3) discuss broader issues associated with yield and productivity growth as an endogenous economic variable.

3. The historical record of yield growth for major annual crops in the united states

3.1. Average annual growth

The average annual yield growth for 11 major annual crops in the United States for the period 1939 to 1994 has been substantial but has varied by crop (Table 1). Sorghum and maize yields have grown at around 3% per annum followed closely by potato (*Solanum tuberosum* L.) and rice at 2.0% to 2.5% per annum. Wheat, barley (*Hordeum vulgare* L.) and cotton (*Gossypium* sp.) yields have grown at about 1.8%, soybean (*Glycine max* L. Merrill) and oats (*Avena sativa* L.) at about 1.25%, and yields of flaxseed (*Linum* sp.) and sunflower (*Helianthus* sp.) seed have grown at about 1.0%. Table 1 provides growth rates for each of these 11 crops calculated using three different methods. The most straightforward method involves calculating the growth from the initial year to the final year as reported in column (3). While straightforward, this approach can be misleading

Table 1
Yield increases expressed as annual growth rates and increments for major US annual crops, 1939–1994

Crop	Annual growth rate (%) using 3 different calculation methods			Annual increment
	(1) Exp. Fit [b]	(2) Linear Fit [c]	(3) Endpoints [d]	(4) Mg ha^{-1} [e]
Sorghum	3.07	3.20	3.41	0.068
Maize	2.85	3.25	2.83	0.118
Potato	2.44	2.46	2.79	0.500
Rice	2.13	2.19	1.71	0.085
Wheat	1.84	1.89	1.78	0.031
Barley	1.83	1.93	1.72	0.037
Cotton	1.83	1.86	1.98	0.009
Soybean	1.25	1.30	1.26	0.021
Oats	1.24	1.24	1.26	0.019
Sunflower [a]	1.08	1.05	0.18	0.013
Flaxseed	0.99	1.15	1.30	0.008

Data Sources: NASS (annual issues) except data for sunflowers which is from. McCormick et al. (1992) prior to 1991 and NASS (annual issues) for later years.
[a] Data for 1962–1993.
[b] The coefficient β_2 in the equation ln $Y_t=\beta_1+\beta_2 t+\varepsilon$, estimated using Ordinary Least Squares (OLS) where Y is yield, ε is the error term, and t is time.
[c] Computed as $(\ln(Y_n^*/Y_0^*))/n$ where Y_t^* is the yield as predicted in time t based on the equation $Y_t^* = \alpha_1 + \alpha_2 t$ where α_1 and α_2 are estimated using OLS and, t=0 is the first year of data and t=n is the last year of data.
[d] Computed as $(\ln(Y_n/Y_0))/n$ where Y_t is the yield in time t where t=n is the final year of data and t=0 is the first year of data.
[e] The coefficient α_2 from the linear equation, see note 3 above.

because yields vary widely from year to year. Thus, if bad weather abnormally depressed yields in the initial year and good weather led to abnormally high yields in the final year, the computed average growth rate can substantially overstate the trend growth or, if reversed, understate the trend. In such a case, choosing slightly different endpoints will give a very different growth rate. The example of sunflower seed yields illustrates this case most clearly: the endpoint calculation method suggests very little growth in yield while other methods indicate an average annual growth of over 1%.

Growth rates in columns (1) and (2) of Table 1 are calculated to eliminate the potential bias introduced by the choice of endpoint. In both columns, growth rates are calculated based on the predicted values for the beginning and end of the sample period over which the trend equations were estimated (see Table 1 notes for the exact approach). Column (1) is based on the assumption that yield growth is a constant average exponential rate. Column (2) is based on the assumption that yield growth is linear; that is, assuming yield growth in terms of output per unit area is, on average, constant over time. The linear prediction implies that the average annual growth rate falls over time and, thus, the average annual growth rate will vary depending on the period over which it is calculated. For example, the estimated linear trend for maize predicts that the annual yield growth fell from 8.7% per year in 1939 to 1.5% per year in 1994. Even the growth rates calculated over the full sample period can vary considerably depending on whether the linear or exponential growth assumption is maintained. For maize, for example, the difference is 0.4% points.

3.2. Incremental yield increases

Calculation of a growth rate assuming a linear trend in yields is somewhat artificial because the calculated growth rate changes depend on the period considered. Moreover, such a summary of yield growth should not be used to extrapolate yields into the future because the assumed underlying trend is linear. The constant factor in the linear model is the absolute increase in yield in Mg ha^{-1}. This estimate, based on the linear trend model, is given in column (4) of Table 1. Potato and to a lesser extent, maize, are both high yielding in absolute terms. Yields for these crops have also experienced high rates of growth. This combination is also reflected as a large absolute average increase in yield in Mg ha^{-1}. Sorghum, while experiencing the most rapid yield growth, generally has a lower absolute yield and thus the average annual incremental yield increase is less than for maize, potato, and rice.

3.3. Is there evidence of a yield plateau?

Brown (1994), examining data on yields for a variety of regions in the world, saw evidence of yield plateaus in the 1980s. Oram and Hojjati (1995), investigating crop yields worldwide also conclude that "growth rates of yields of all major cereals have stagnated or declined overall in most developing and developed regions during the 1980s." To test whether there is any evidence of yield plateaus in the US, we examine three time trend formulations to determine which provides a better fit of the data (Table 2), as follows:

(1) exponential growth in yields, $Y_t = \exp(\beta_1 + \beta_2 t + \varepsilon)$;
(2) linear growth, $Y_t = \alpha_1 + \alpha_2 t + \varepsilon$; and
(3) logarithmic growth, $Yt = \ln(\gamma_1 + \gamma_2 t + \varepsilon)$

where Y_t is yield in time t, and, ε is the error term. The logarithmic formulation assumes that the absolute increment to yield growth falls over time but that the yield growth never actually falls to zero. Comparison of goodness of fit among the three models for each of the 11 crops shows little support for the logarithmic growth assumption (Table 2). It provides the best fit only in the case of flaxseed yield. Flaxseed yield has been highly variable in the US. As a result, none of the trend models fit the data very well. In the case of cotton, the logarithmic model does better than the exponential model but poorer than the linear model. In all other cases the logarithmic model provides the poorest fit of the three models and in many cases it performs substantially poorer. In the case of potato and maize, where the exponential and linear trend models explain over 90% of the sample variation, the logarithmic model explains only 10% and 30% of the variation. Statistically, the logarithmic formulation is not significantly better for any of the

Table 2
The evidence for yield plateaus: relative fit of alternative trend assumptions for 11 major US annual crops, 1939–1994

Crop	R^2 for OLS Fitted Trend Equations			Significance of Difference Z-test statistic [e]		
	(1) Exponential [b]	(2) Linear [c]	(3) Logarithmic [d]	(1) vs. (2)	(2) vs. (3)	(1) vs. (3)
Sorghum	0.842	0.876	0.717	−0.666	2.344*	1.678
Maize	0.926	0.917	0.378	0.305	6.117*	6.421*
Potato	0.901	0.979	0.107	−4.057*	11.625*	7.568*
Rice	0.913	0.944	0.725	−1.165	4.378*	3.213*
Wheat	0.903	0.917	0.870	−0.417	1.209	0.793
Barley	0.917	0.905	0.797	0.361	2.091*	2.452*
Cotton	0.842	0.853	0.843	−0.200	0.182	−.018
Soybean	0.867	0.849	0.720	0.349	1.772	2.121*
Oats	0.794	0.793	0.753	0.014	0.376	0.526
Sunflower [a]	0.349	0.341	0.318	0.039	0.152	0.151
Flaxseed	0.354	0.404	0.414	−0.334	−0.067	−.401

[*] Correlation is significantly different at the P =0.05 level (critical value, 1.96).
[a] Data for 1962–1993.
[b] The equation was $Y_t{=}\exp(\beta_1{+}\beta_2 t{+}\varepsilon)$, estimated using Ordinary Least Squares (OLS) where Y_t is yield, ε is the error term, and t is time. To estimate using OLS, the equation was transformed by taking the logarithm of both sides.
[c] The equation was $Y_t{=}\alpha_1{+}\alpha_2 t{+}\varepsilon$.
[d] The equation was $Y_t{=}\ln(\gamma_1{+}\gamma_2 t{+}\varepsilon)$. To estimate using OLS, the equation was transformed by taking the exponential function of both sides.
[e] Significance of correlation computed as a Z-test for two correlation coefficients, see Kanji (1993). A negative value indicates that the second equation in the comparison is more highly correlated and, if the absolute value of the statistic is greater than the critical value, the second equation is significantly better than the first; e.g., in comparison of (1) vs. (2) (exponential vs. linear), the linear form fit significantly better than the exponential form for potato.

11 crops and for six of the crops (all major grains, potato, and soybean) either the linear or exponential (or both) formulation provides a significantly better fit at the $P=0.05$ level [Table 2, comparisons (2) vs. (3) and (1) vs. (3)].

The logarithmic specification, while not generating an absolute yield plateau, is still a relatively severe formulation if one's view is that the annual *growth rate* of yield is constant. In this regard, a linear trend in yields, generating a falling growth rate over time, could be considered a weaker form of yield plateau. The data, however, provide very little ability to judge whether the exponential or linear model provides a better fit for yield growth in the United States among the 11 crops considered. For five crops, the linear model provides the best fit and for five crops the exponential model provides the best fit. With the exception of potato, none of these differences are, however, statistically significant at the $P=0.05$ level.

The popular argument that ''yields cannot continue to grow exponentially forever'' suggests the hypothesis that a crop where yield growth had been particularly rapid may have moved nearer to its biological yield potential and thus we may be more likely to see evidence of slowing yield growth. There is, however, little support for this hypothesis in the data. For example, among the two crops with the highest yield growth, maize and sorghum, the exponential trend model fits the maize data better while the linear model fits sorghum better. Similarly, their is no consistent picture for crops that have had moderate or slow growth with respect to whether the linear or exponential model provides a better fit.

Another approach for testing for a yield plateau is to estimate the model, $Y_t=\zeta_1+\zeta_2 t+\zeta_3 t^2+\varepsilon$. If ζ_3 is significantly positive then the implication is that the yield trend is increasing at an increasing rate (i.e., that the absolute increment is increasing over time). If ζ_3 is significantly negative then it would indicate that the rate of absolute increase is declining over time. Ordinary Least Squares (OLS) regression was used to estimate this model for 10 crops (excluding sunflowers). The coefficient, ζ_3, was significantly positive for maize and soybeans and significantly negative for flax. For rice, oats, cotton, sorghum, and wheat the sign was negative but the coefficient was not significant at the $P=0.05$ level. For barley and soybeans the sign was positive but not significant. These results closely parallel the functional form tests reported in Table 2.

4. Extrapolating yield trends: implications for crop yields in 2020

4.1. Linear versus exponential extrapolation

Extrapolating trends into the future is a risky undertaking. Unfortunately, the inability to foresee innovations in and the diffusion of new technology has led many forecasting efforts to rely principally on yield trend extrapolation. As documented above, whether one characterizes yield growth as linear or exponential affects the interpretation of historical average annual growth. The effects on future yields, extrapolated 25 years into the future, is far greater as demonstrated in Fig. 1 and Table 3. We do not present extrapolations based on the logarithmic model because the model fit is poor. For crops where yields have been growing more rapidly (sorghum, maize, potatoes, rice), extrapolating exponential growth rates implies that yields double or more than double by 2020. In contrast, extrapolating the linear model implies that by 2020 yields increase by about only about 50% for these same crops. Consistent with the formulation, the linear models imply a significant slowing of the growth rates of yields. The implied growth rate from 1994 to 2020 falls from an average of 3.2% to 1.4% for sorghum, from 3.2% to 1.3% for maize, from 2.5% to 1.2% for potato, from 2.2% to 1.1% for rice, from near 2.0% for wheat, barley, and cotton to 1.0%, and from around 1.0% to 1.3% to 0.7% to 0.8% for soybean, oats, sunflower, and flax. These comparisons are based on the linear model; i.e., the historical growth rate as derived from the linear model predictions (column 2 in Table 1) and the linear model prediction of yield for 1994 (Table 3) is used as the 1994 base to calculate the average annual growth through 2020. Table 4 provides further details on the results of these regressions.

4.2. Sources of yield increase and projection caveats

A significant amount of analysis dating to the early 1980s focused on trying to explain the contribution of genetic improvement to yield growth (e.g., Fehr, 1984). These previous attempts to determine the sources of crop yield growth have relied primarily on two types of approaches. Agronomists have compared yields of old and new cultivars grown side-by-side under a set of optimal conditions for each variety. The difference in yields between old and new varieties are then compared to changes in farmers yields over the same time period to determine the share of actual yield improvement that could be attributed to genetic improvement. Economists have used a second approach in which multiple regression analysis is used to associate changes in farm yields to changes in variety, fertilizers, pesticides, and other inputs.

Using the agronomic approach, Duvick (1984) reported that between 1930 and 1980 the maximum yield potential of hybrid maize increased by 4.6 Mg ha^{-1}, or more than double the 1930 level (Duvick, 1984). This is equivalent to 89% of the gain in maize yields achieved by Iowa farmers over this period. Miller and Kebede (1984) found that sorghum yield potential increased by 1.6 tons per hectare, or 63% of the total change in average farmers' yields, between 1950 and 1980. For soybeans, Specht and Williams (1984) estimated that genetic improvement improved yields by 1.41 Mg ha^{-1} between 1902 and

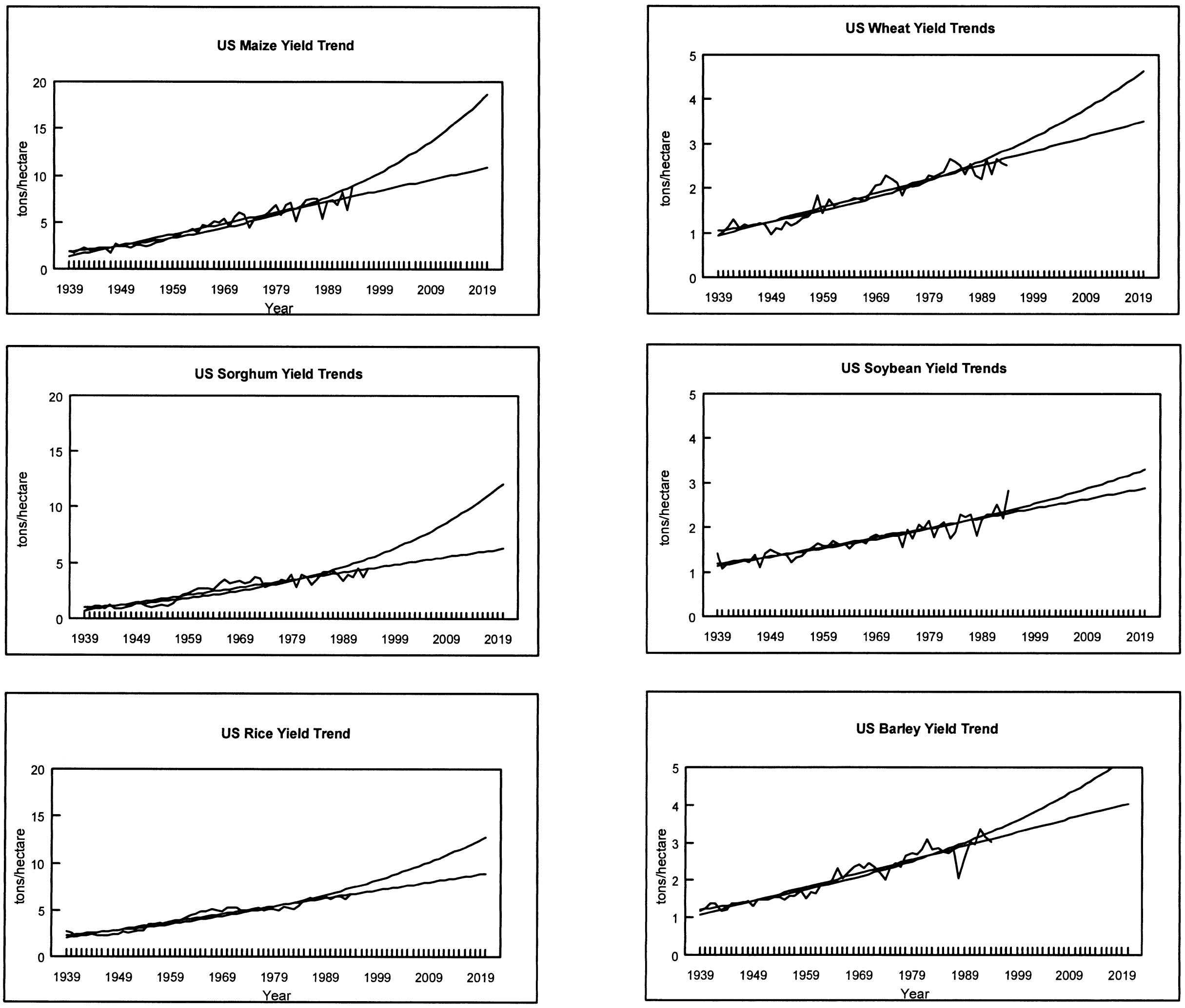

Fig. 1. Yield (Mg ha^{-1}) trends for 11 major US crops. Note: Actual historical yields are production divided by area harvested. Trend and trend projections are based on linear and exponential time trend fitted using Ordinary Least Squares (OLS) regression.

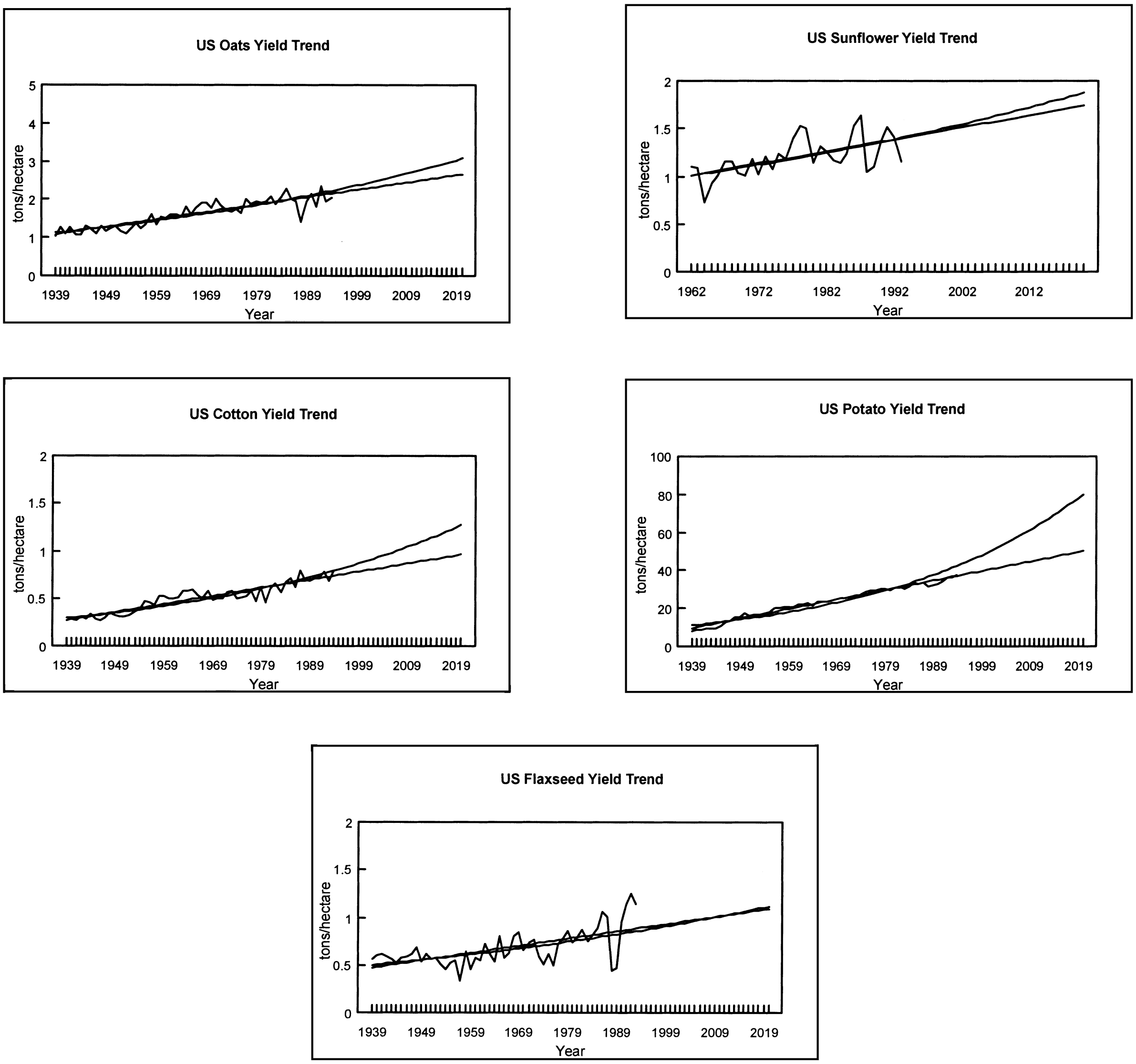

Fig. 1. (Continued)

1997, or by 90% of soybean yield gains realized by farmers. Meredith and Bridge (1984) determined genetics caused cotton lint yields to increase by 250 kg ha^{-1} between 1936 and 1960, equivalent to 67% of farm-level cotton yield gains during this period. Schmidt (1984) estimated that 50% of wheat yield gains between 1958 and 1980 were due to breeding. However, this approach may overestimate the contribution of genetic changes to changes in farmers' yields since it does not take into account changes in the use of other inputs, such as fertilizers and irrigation. Farmers' yields are often below the maximum potential yield of a variety due to economic, management, and biophysical factors. Moreover, over time the location of production may shift to marginal areas or concentrate in favorable ones. Walker (1994) attributed virtually all of the growth in US potato yields during the 20th century to improved agronomic methods and the concentration of production in the most favorable environments. Lynch and Frey (1993)

Table 3
Predicted crop yields (Mg ha^{-1}) based on the exponential and linear models, 1939, 1994, and 2020

Crop	1939		1994		2020	
	Exponential	Linear	Exponential	Linear	Exponential	Linear
Sorghum	1.00	.78	5.44	4.53	12.08	6.30
Maize	1.85	1.30	8.88	7.78	18.64	10.85
Potato	11.05	9.59	42.38	37.12	80.00	50.12
Rice	2.27	2.00	7.34	6.68	12.78	8.89
Wheat	1.04	0.94	2.86	2.67	4.62	3.49
Barley	1.20	1.07	3.29	3.09	5.29	4.05
Cotton	0.29	0.26	0.79	0.74	1.27	0.96
Soybean	1.19	1.13	2.38	2.32	3.29	2.88
Oats	1.12	1.09	2.23	2.16	3.07	2.66
Sunflower [a]	1.01	1.01	1.41	1.40	1.88	1.74
Flaxseed	0.50	0.47	0.87	0.90	1.12	1.09

[a] Data for 1962, 1993, and 2020 reflecting the limited time series on sunflower production.

concluded that in the eight decades prior to 1988, the principal contribution of oat breeding in the US was to develop varieties with greater tolerances for stressful environments, with very little yield growth registered.

Using multiple regression analysis, Thirtle (1985) estimated the contribution of biological inputs to the growth in farmers' yields, after accounting for changes in fertilizer, labor, machinery, and land use and allowing for substitution among inputs. Biological inputs included the use of improved varieties and changes in agronomic practices such as plant density and seeding rate; the type, concentration, and timing of fertilizer applications; changing tillage practices for improved weed control and soil tilth; and changing crop rotations. Thirtle (1985) estimated that between 1939 and 1978, biological inputs increased maize yields by an average of 1.7% per year, wheat yields by 1.5%, soybean yields by 1.1%, and cotton yields by 0.5%. Compared with total yields realized by farmers over this period, biological inputs accounted for 50% of the yield growth in maize, 85% for soybeans, 75% for wheat, and 24% for cotton. Other studies using a similar methodology have estimated that genetic improvement in wheat contributed to about 50% of yield gains over roughly the same period (Dalrymple, 1980). One limitation of this type of analysis is that data on all of the important production inputs may not be available. Cardwell (1982) drew upon a wide assortment of statistical information on changes in farm production practices to identify sources on maize yield increases in Minnesota between 1930 and 1979. He considered not only seed type and seeding rate, fertilizer and pesticide use, but also changes in seeding date and seeding method, tillage, manure use, cropping patterns, soil drainage, mechanization, the spread of insect problems such as the corn borer and corn rootworm, and weather patterns. Together, these technical changes increased Minnesota maize yields from 2.0 to 6.3 Mg ha^{-1} over this 50-year period. Cardwell (1982) estimated that improved cultivars accounted for 58% of yield increases, and that collectively, changes in agronomic practices were responsible for about 25% of yield gains. Yield improvements due to fertilizer were partially offset by a reduction in manure and organic matter.

These estimates vary considerably for different crops and for the same crop during different periods. Technological advances often occur unevenly. Occasionally, a major technological breakthrough results in rapidly increasing yields for some years, but then yield growth slows until another major advance takes place. The discovery of economical methods of hybridization led to dramatic increases in maize yields after the 1930s that have continued up to the present time. Sorghum yields doubled in the 1960s when hybrids were first introduced, but yield growth has slowed since then. The introduction of hybridization methods in soybean breeding in the 1940s led to a rapid jump in cultivar yields. The introduction of semi-dwarf wheat and rice varieties helped to raise the yields of these crops in the 1960s and 1970s. Cotton yields increased significantly in the 1950s, were stagnant between 1960

Table 4
Fitted yield trends results based on three models for 11 major US crops, 1939–1994

Crop	Model	t Coefficient [b]	Standard Error for Y	R^2
Sorghum	Exponential	0.031 (0.002)	0.22	0.84
	Linear	0.068 (0.003)	0.42	0.88
	Logarithmic	1.25 (0.107)	12.9	0.72
Maize	Exponential	0.028 (0.001)	0.13	0.93
	Linear	0.119 (0.005)	0.58	0.92
	Logarithmic	38.3 (6.69)	808.7	0.38
Potato	Exponential	0.024 (0.001)	0.13	0.90
	Linear	0.500 (0.010)	1.22	0.98
	Logarithmic	7.74×10^{13} (3.04×10^{13})	3.67×10^{15}	0.11
Rice	Exponential	0.021 (0.001)	0.11	0.91
	Linear	0.085 (0.002)	0.34	0.94
	Logarithmic	10.4 (0.873)	105.6	0.73
Wheat	Exponential	0.018 (0.001)	0.10	0.90
	Linear	0.031 (0.001)	0.16	0.92
	Logarithmic	0.205 (0.011)	1.31	0.87
Barley	Exponential	0.018 (0.001)	0.09	0.92
	Linear	0.037 (0.002)	0.20	0.91
	Logarithmic	0.342 (0.023)	2.84	0.80
Cotton	Exponential	0.018 (0.001)	0.13	0.84
	Linear	0.009 (0.001)	0.06	0.85
	Logarithmic	0.014 (0.001)	0.10	0.84
Soybean	Exponential	0.013 (0.001)	0.08	0.87
	Linear	0.022 (0.001)	0.15	0.85
	Logarithmic	0.135 (0.011)	1.39	0.72
Oats	Exponential	0.012 (0.001)	0.10	0.79
	Linear	0.019 (0.001)	0.16	0.79
	Logarithmic	0.101 (0.008)	0.95	0.75
Sunflower[a]	Exponential	0.011 (0.003)	0.14	0.35
	Linear	0.013 (0.003)	0.17	0.34
	Logarithmic	0.043 (0.011)	0.60	0.32
Flaxseed	Exponential	0.010 (0.002)	0.22	0.35
	Linear	0.008 (0.001)	0.15	0.40
	Logarithmic	0.017 (0.003)	0.33	0.41

[a] Sample for 1962–1993.
[b] Standard errors are in parentheses.
The estimated models: exponential growth, Y_t=exp($\beta_1+\beta_2 t+\varepsilon$); linear growth, $Y_t=\alpha_1+\alpha_2 t+\varepsilon$; logarithmic growth, Y_t=ln($\gamma_1+\gamma_2+\varepsilon$) where Y_t is yield in time t and ε is the error term β_2, α_2, γ_2 are the t coefficients (time trend terms).

and 1980, and since 1980 have achieved steady increases. Plant breeding, like all research endeavors, is an uncertain and risky undertaking in which successes are difficult to predict.

The further step needed to describe how genetic improvements relate to actual commercial yield improvements is to describe the diffusion of the genetically improved varieties and the actual performance of those varieties under varying commercial, climatic, and resource conditions. Changes in a number of aggregate factors can contribute to improved yields or can offset genetic improvements. Area expansion of the crop over time into more marginal areas or, conversely, concentration and specialization of areas most productive for a given crop would contribute to average yield declines or increases (Dalrymple, 1980). Similarly, changes in resource quality through processes that contribute to land degradation (soil loss, compaction, loss of fertility) or land improvements (drainage, soil conservation) could contribute negatively or positively to average commercial yield. And, factors such as expansion of irrigation, improved technologies for pest control, and generally improved farm management can be major sources of yield increase that are partially or fully 'controlled' out of experimental farms or other controlled samples of farms.

Given the problems of describing the structural details of this process, focusing directly on national average yields has some advantages if one is interested in projecting yields into the future for the nation or a significant portion of the nation. Ideally, these factors could be separately accounted for, modeled, and future projections could then consider how future trends in these factors may differ from historical trends. Data for considering all of these factors is not available and, once controlled for, the development of future projections of these variables would require further consideration. Such a potentially useful exercise is beyond the scope of this paper.

5. Is it biologically possible to obtain extrapolated yields?

Simple extrapolation is rarely satisfying. A significant challenge to yield extrapolation is to consider whether it is biologically possible to achieve extrapolated yield levels. The inability to foresee major innovations means that a failure to demonstrate that the biological potential exists to obtain extrapolated yields does not necessarily rule out the possibility that such yields might indeed be achieved. Still, a projection period of 20 to 25 years is not so long that one might not hope to see evidence of the biological foundations for further increases.

A few recent efforts have attempted to provide a better understanding of the potential sources of future increases in crop yields (Ruttan, 1989; Easterling et al., 1993; Oram and Hojjati, 1995; Bumb, 1995; Plucknett, 1995; Duvick, 1995). Several of these analyses are directed toward yields worldwide with a particular interest directed toward yields in developing countries. The broader issues raised by these efforts are, however, generally applicable.

5.1. Categories of consideration

There are a number of ways to think about the potential for commercial yields to increase. Work at the International Rice Research Institute (IRRI) illustrates the different types of gaps and yield ceilings that have been identified for rice in southeast Asia (Plucknett, 1995). As the first panel in Fig. 2 illustrates, a substantial gap may exist between the average farm yield and the theoretical crop yield. Intermediate gaps defined as simply the difference between the categories: i.e., between existing on-farm yields and practical farm yields if cropping is well-managed; between practical farm yields and yields achieved at experiment stations under highly managed conditions; and between average experiment station yields and record yields when weather conditions and practices are near ideal, were also identified. While the existence of such gaps offers evidence that additional yield gains are achievable or at least not biologically foreclosed, to achieve these higher yields may still require considerable research and development effort. Plucknett (1995) relates each of these gaps to specific types of research tasks. The three main research tasks he identifies are (1) sustain present yields, recognizing that without maintenance research yields will erode, (2) closing yield gaps, and (3) increasing the yield ceiling. In this interpretation, one cannot take for granted current yields or the easy transfer of best yields from research stations or top farms to the bulk of commercial producers. But, neither are currently perceived yield ceilings an ultimate barrier.

Another approach is to consider potential biophysical sources for future crop yield. The following considerations are drawn from Ruttan (1989).

- There remains unexploited potential for paying attention to soil, water, other environmental factors. Most attention to date has been on genetic factors.
- It is possible to get higher yields with current technology by improving the management of the production process.
- Many of the past yield gains have resulted from increasing the harvest index (grain to straw ratio). There is evidence that this opportunity has been largely exploited. Jain (1986) presented evidence for five major crops indicating that much of the yield gain has been due to increases in the harvest index.
- In light of the limited potential for further increases in the harvest index, there is need to work on improving other aspects of plant growth and yield such as focusing on increasing the photosynthetic rate.

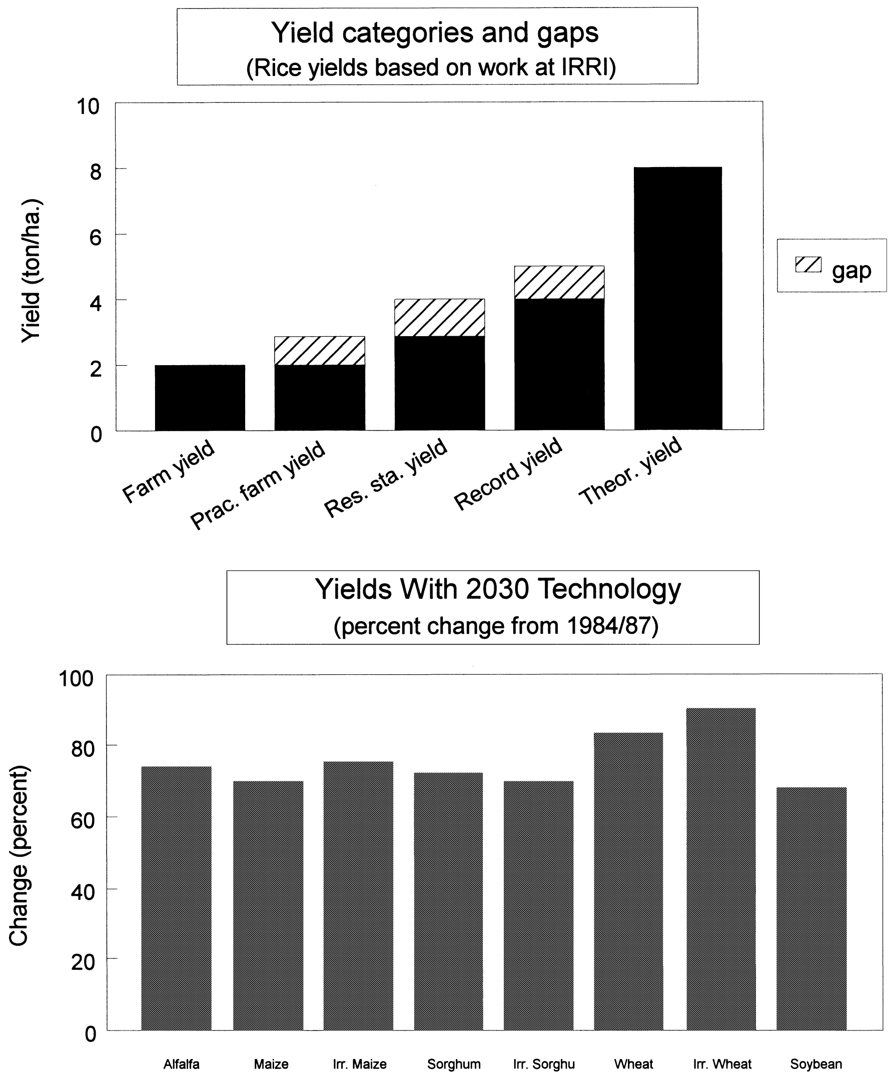

Fig. 2. Yields, yield gaps, and potential future yields. Sources: Yield categories and gaps are from Plucknett (1995). The illustrated yield 'gaps' are the difference between the yield category and the previous category; i.e., the gap between the 'practical farm yield' and actual 'farm yield', 'research station yield' and 'practical farm yield', and so forth. Yields with 2030 technology is from Easterling et al. (1993).

Easterling et al. (1993) based in part on some of the above observations simulated changes in plant growth and yield as modeled by the Erosion Productivity Impact Calculator (EPIC). Their simulations were intended to show how crop yields could change through the year 2030 in the four state area, Missouri, Iowa, Nebraska, and Kansas. Within EPIC they judgmentally changed the following factors:

- the harvest index,
- photosynthetic efficiency,
- pest management,
- leaf area, and
- harvest efficiency.

These changes were simulated for alfalfa (*Medicago sativa* L.) and soybeans under dryland production and for maize, sorghum, and wheat under both dryland and irrigated conditions. Panel 2 of Fig. 2 illustrates the yield changes that they simulated. Overall, they found it possible to simulate a yield increase of around 70% or more for each crop. These yield increases are equivalent to a 1.3% to 1.6% per year rate of exponential growth.

5.2. *Will these yield increases occur?*

There is a long history in economic projection models of assuming that technical change is an exogenous factor. Models and analyses projecting future production and consumption or future economic growth, typically assume an exogenous productivity trend. Hayami and Ruttan (1985) have been responsible for generating a literature demonstrating that the technical change responds to economic factors such as relative factor prices. It has, however, proved difficult to introduce this factor into economic forecast models because it has been difficult to isolate technical change and the diffusion of technology from input substitution and investment in known technologies as input prices change. Work to estimate the rate of return to public agricultural research also clearly shows a strong association between the amount of research investment and the change in agricultural productivity; estimates indicate that the marginal rate of return on public agricultural investment is at least 35% (Fuglie et al., 1995). Again, this is clear evidence that the productivity gain in agriculture is not an exogenous factor but depends in large part on the level of research investment from both public and private sources. While difficult to separate from technical change, economic modeling and economic evidence suggests that changing relative input and output prices and incentives lead to different levels of management and input use which, in turn, affects yield. A slowing of yield growth in the 1980s, to the extent it occurred, may in part be due to low output prices for commodities. The cross-country evidence, high yields in Europe with the Common Agricultural Policy (CAP) that created high prices for wheat and (apparent) high rice yields in China where there were strong incentives to be self-sufficient in rice production, suggest the power of strong incentives for increasing yields. Finally, yield growth (crop production per hectare) is in economic terminology a partial factor productivity measure. The long term history of technical change, first mechanical innovations that saved labor and secondly, (only in this century) significant yield enhancements that saved land, may be partly a coincidence of how technology was discovered. The induced innovation hypothesis also explains the pattern. In the 1700 and 1800s labor was the relatively expensive component of production (it required most of the population to feed itself) while there was much land available. In the 1900s, land has become relatively more scarce and technology has responded with land-saving (yield increasing) innovation. The trend in the next century may be a focus on improving 'environmental' productivity. That is, reducing the environmental impact of agricultural production. If so, yield growth in terms of output per hectare may be sacrificed to achieve increased yield growth per unit of environmental damage. Exactly how this would play out, is however, highly uncertain: yield growth per hectare may be consistent with yield growth per unit of environmental damage if it means that land area devoted to crop production need not expand or could contract thereby saving preserving larger areas of natural ecosystems.

Yield growth, particularly over a longer period of 10 or 15 years after which current technology that is in the pipeline is in the field, depends on a number of factors, including:

- future levels of public agricultural research in the US and worldwide
- private research funding, which depends on the extent to which private firms can profit from innovations. The ability to profit from innovations depends on how intellectual property rights are defined and protected and on the prices of crops which creates a derived demand for innovations.
- future input and output prices, including the pricing and incentives that exist to reduce environmental damages stemming from crop production.

The interdependence of economic systems, yield and commodity supply interacting with changes in demand to determine price but changes in price also affecting yield and technical change, requires a simultaneous solution of the system to determine yield. Unfortunately, that simultaneous model is not completely specified. If technical change and yield are quite responsive to economic signals then the job of forecasting future yields requires that much attention be paid to population and income growth. This is quite the opposite of the more common approach that considers yields as exogenously determined and prices, cropped area, and consumption endogenously changing given the yield constraint. A useful theoretical and proposed empirical approach for integrating innovation and technology choice to better predict future production is provided in Antle (1996).

6. Conclusions

Yield growth for 11 major annual crops in the US has been rapid since 1939 ranging, across crops, from about 1% per year on average to over 3% per year. There is no evidence that yields plateaued for these crops in the US in recent years in the strict sense that yield growth in absolute terms has slowed or stopped. It is not possible to argue strongly that a linear model of yield growth (constant annual absolute increases in yield) or an exponential model of yield growth (a constant rate of growth of yield) provides a significantly better fit of the data. In simple extrapolation exercises, however, which of these models one chooses has a large difference for future yields in 2020. Adopting the linear model to extrapolate yields implies that the average annual growth rate for the 11 crops between 1994 and 2020 would range from about 0.7% to 1.3% per year, considerably slower than if the historical rate of growth (1% to 3% per year) is projected to continue.

There do not appear to be obvious biological limits that would prevent yields from reaching the extrapolated levels, at least in the case of linear extrapolations. There are a number of avenues by which crop yields could be increased. Ultimately, however, crop yield and agricultural productivity depend on the levels of public and private research and development (R & D) and future crop and input prices. A positive trend in recent years is the large increases in private R & D, possibly in response to strengthening of intellectual property rights. Public R & D has grown at a slower pace. There has been much rhetoric about the need to focus more attention on improving the environmental performance of agricultural technology and a variety of policy incentives with the intent of encouraging environment and resource conserving technology adoption. The evidence in terms of the changing share of public research expenditures devoted to different categories of research does not show such a shift but these gross categories may be a poor indicator of where the attention of individual scientists is directed. Whether, and the extent to which, an increased focus on the environment implies a trade-off with yield growth is unclear and will depend on the type of environmental incentives put in place.

While forecasting yield trends is fraught with many difficulties and future yields depend on many factors which cannot easily be predicted, there is no convincing evidence that yield growth over the next 20 years will fall much below a linear trend. The more optimistic case is that yield growth will continue to grow at the rapid exponential rates seen over the past 45 years. These results suggest that default yield growth rates for purposes of forecasting SOC of 0.7% to 1.3% per annum would be conservative, based on a linear growth trend. The more optimistic case assumption of yield growth operating as an exponential growth function could lead to yield increase of up to 3% per year if historical rates persist. Such rates of growth could lead to substantial increases in soil carbon if crop residues remain on the soil.

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